

**ACOUSTIC SCATTERING CLASSIFICATION OF ZOOPLANKTON AND
MICROSTRUCTURE**

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ABSTRACT

The long-term goals of this research were to understand the acoustic reverberation properties of zooplankton and microstructure and to apply these models, along with advanced instrumentation, to further our understanding of biological and physical processes in coastal and open ocean areas. The approach involved a combination of laboratory and *in situ* measurements of scattering by individual zooplankton, development of acoustic scattering models, development of broadband physics-based classification and signal processing techniques, surveying coastal waters with advanced instrumentation, and development and use of methods for discrimination between, and quantification of, the spatial and temporal patterns of biological and physical processes. Numerous papers were published in peer-reviewed scientific journals and many presentations were made at open conferences. The results were also summarized in books and book chapters. Impact on the scientific and navy communities was significant.

LONG-TERM GOALS:

To understand the acoustic reverberation properties of zooplankton and microstructure and to apply these models, along with advanced instrumentation, to further our understanding of biological and physical processes in coastal and open ocean areas.

SCIENTIFIC APPROACH:

The research was a balance of experimentation in the laboratory and in local waters, development and refinement of acoustic scattering models of zooplankton and microstructure, development of broadband physics-based classification and signal processing techniques, surveying coastal waters with advanced instrumentation, and development and use of methods for discrimination between, and quantification of, the spatial and temporal patterns of biological and physical processes.

SUMMARY OF RESULTS:

The results of this research are presented in detail in the open literature publications listed at the end of this report. The results are summarized as follows:

Fundamental advances have been made on

1) Controlled measurements of acoustic scattering by zooplankton.

Interpretation of acoustic scattering data requires understanding the fundamental scattering processes. Given the complexity of the scatterers (zooplankton and microstructure), modeling of the scattering

requires controlled measurements of the scattering in order to identify dominant scattering mechanisms and to sometimes empirically determine key model parameters.

Prior to this project, acoustic scattering measurements had been conducted in the laboratory on individual zooplankton. Although much of the physics of the scattering had been revealed, there had been no control over orientation of the individual, an important modeling parameter. Furthermore, all data had been collected near the surface of the water, which left the question of the depth-dependence of the scattering of gas-bearing organisms. Laboratory measurements. Our laboratory measurements at WHOI in this project involved measuring the acoustic backscattering over all angles of orientation in two planes of rotation and in one-degree increments. The measurements were made for two major classes of organisms, fluid-like (decapod shrimp) and elastic shelled (periwinkles, chosen for their similarity to certain shelled zooplankton), and over the frequency range 24 kHz - 1 MHz. Some of the acoustic sensors were broadband. The resultant data revealed the dominant scattering mechanisms as a function of angle. For example, at certain orientations, the acoustic echo from inside the opercular opening of the elastic-shelled organism was significant. In situ measurements. In addition, *in situ* measurements of acoustic backscattering were made of gas-bearing zooplankton (siphonophores) freely swimming at their natural depth by use of a remotely operated vehicle (ROV) with co-located acoustic and video sensors. These results demonstrated the importance of the gas to the scattering, even at depths deeper than experienced in the laboratory.

2) Acoustic scattering models of zooplankton.

Using the results of the controlled measurements of acoustic scattering by various organisms, the acoustic scattering models were significantly advanced. a) Fluid-like organisms. The models involving the fluid-like organisms (such as decapod shrimp and euphausiids) are now quite mature and reliable over a wide range of conditions. The modeling of that class of organism was based on the acoustic measurements that span a wide range of orientations and frequencies, as well as three-dimensional morphological information on the organisms derived from computerized tomography (CT) scans of the organisms. The scattering model, using the Distorted Wave Born Approximation (DWBA), is a three-dimensional integral using the three-dimensional morphological information. The model was tested over a wide range of conditions, confirming its range of validity. b) Elastic-shelled organisms. The modeling of the elastic shelled organisms involved advances in both the ray-based models as well as one that describes the scattered energy averaged over orientation. Since the laboratory measurements revealed significant scattered rays arising from the front interface, a Lamb circumferential wave, and a ray scattered from inside the opercular opening, a new model was developed to incorporate those rays. The ray theory involved single-ping, single-orientation data. In order to emulate field conditions where the orientation of the organism spanned a range of orientations, a modal-series solution for spherical shells was adapted to the problem and shown to provide reasonable accuracy over a wide range of acoustic frequencies. c) Gas-bearing organisms. A scattering model was developed that incorporated effects due to the tissue as well as gas. A key parameter was the size of the (gas) pneumatophore of the siphonophore, which was determined from measurement after capture at 1 Atm pressure and through verification when modeling the scattering by the organisms at their natural depth.

3) Broadband signal processing methods.

Through use of a cross-correlation technique, broadband acoustic echoes were temporally compressed, allowing dominant scattering features of the organisms to be resolved in the along-range direction. This analysis allowed direct confirmation of scattering features inferred through previous analyses of the interference patterns in the broadband spectral data. This powerful approach was used both as a tool for developing the scattering models described above, but was also used as a classification technique as described below. A distinct advantage of using this temporal technique over other spectral methods is the

inherent improvement in the signal-to-noise ratio (this method is similar to the well-known matched filter method).

4) Broadband acoustic classification methods for individual zooplankton.

Two methods were developed, one involving the spectral domain and the other in the time domain. a) Spectral domain. Each broadband echo from a given organism had a characteristic pattern specific to the anatomical group, size, and orientation. The spectrum typically had a series of peaks and nulls. Although all spectra had these features, regardless of animal type, the statistical behavior of the spectra varied with animal type. Methods were developed using both data and models to describe the statistical behavior and to discriminate between animal types, given an ensemble of broadband echoes. b) Time domain. Using the pulse-compression processing of the broadband echo described in the previous section, the resultant time series contains peaks correlated with dominant scattering features of the organism. All compressed pulse signals appeared broadly similar, containing a series of peaks. However, the separation between the peaks was shown to have significant differences, statistically, between animal types.

5) Surveys of zooplankton and microstructure with advanced instrumentation.

Through ONR DURIP funding (reported elsewhere), a significant advanced sensor platform and associated control van, winch, and handling system was purchased for use in this program. The system, towable from a ship, contained acoustic backscatter transducers (43 kHz - 1 MHz) looking in the upward and downward directions, a video plankton recorder (VPR), bio-optical sensors matched to those of the SeaWiFS satellite to measure water properties, and various environmental sensors including a CTD, fluorometer, and transmissometer. The system was used in five cruises in the Gulf of Maine and Georges Bank area. Other measurements were conducted at the same time with a MOCNESS zooplankton net system and a vertical cast CTD. These surveys provided an unprecedented first-of-a-kind set of data in which all data were co-located, all sampled at high resolution, and all continuously sampled over scientifically interesting coastal regions. The data revealed that, depending upon the depth and location, the dominant source of acoustic scattering varied from organism to organism and was sometimes from physical microstructure.

6) Interpretation of surveys.

The combination of acoustical, video, and environmental sensors provided high-resolution information on the spatial variability of various zooplankton and, in some cases, physical microstructure. With the broad frequency coverage of the acoustical sensors, discrimination and quantification of the dominant scatterers was possible. Since the scattering signature is different for the different types of scatterers, microstructure scattering was differentiated from scattering by organisms in a region where there was significant near-surface mixing. Dissipation rate of the microstructure and size of euphausiids below the microstructure were estimated from the scattering data. In another area, the presence of siphonophores was quantified. These fragile organisms are generally undersampled by nets as nets shred them. However, the combination of acoustics and the VPR demonstrated the presence of a significant layer of these organisms. The data also revealed a layer of their prey directly below them.

SIGNIFICANCE AND IMPACT ON THE COMMUNITY

Before this research program began, a common misunderstanding in the ocean research community was that the strength of the acoustic echoes from aggregations of marine organisms increased monotonically with biomass. That is, the presence of more biomass gave rise to a larger echo. Our studies demonstrate definitely that this generally is not true except in very special cases where monosize monospecies are

present. For example, we demonstrated that shelled organisms scattered sound 19,000 times more efficiently than certain common gelatinous organisms. Thus a patch of small, shelled zooplankton with relatively little total biomass can dominate the echo when co-occurring with gelatinous organisms with larger total biomass. Using the scattering models, advanced instrumentation, and associated processing methods developed in this program, we have demonstrated the means by which the complex echoes from mixed aggregations of zooplankton can be interpreted. The methods involve discrimination between gross anatomical groups of organisms, discrimination between organisms and microstructure, and interpretation of the echoes in terms of meaningful biological and physical parameters.

One major outcome of our studies involved quantification of the presence of siphonophores, a fragile gas-bearing organism. Because of their fragility, these organisms are commonly grossly undersampled as they are shredded by nets. However, by use of our acoustical and video sensors, along with scattering models, we have been able to detect and quantify layers of siphonophores, an important predator of smaller zooplankton.

The impact and transitions due to our research are summarized as follows:

- 1) Our acoustic scattering models are being used around the world by marine scientists. Their use has either involved applying software that we have sent them or has been through their developing their own software based on the equations we published in the open literature.
- 2) Our acoustic scattering models have been used by Navy laboratories in predictions of sonar performance. There is one high frequency acoustics Navy system in operation today (the "standoff system") whose design is based, in part, on our scattering models. Furthermore, our models have been used by the company SAIC to explain some false targets of the MK48 ADCAP torpedo that could not otherwise be explained by returns from the seafloor and sea surface. In addition to direct use of the zooplankton models, the Navy has adapted the deformed cylinder formulations that had served as a basis for the zooplankton models, to model acoustic scattering by submarines.
- 3) The models developed for shelled zooplankton for this project have been adapted to describe the acoustic scattering by a shell-covered seafloor. The results have led to an explanation, to first order, of the acoustic scattering by a shell-covered seafloor in the ONR SAX99 program.

NOTABLE AWARDS OR RECOGNITION OF SCIENTIFIC PERSONNEL DURING THIS PERIOD:

Appointment: Dr. Andone Lavery from Post-Doctoral researcher to Assistant Scientist at WHOI

Promotion: Dr. Dezhang Chu was promoted to Research Specialist at WHOI

Chairs:

- 1) Stanton was chair of the Department of Applied Ocean Physics and Engineering
- 2) Stanton was chair/organizer of a scientific meeting of The Oceanography Society (2001)
- 3) Stanton was co-chair/co-organizer of The Oceanography Society/Oceanology International Americas Ocean Conference for 2003
- 4) Wiebe was chair of US GLOBEC Georges Bank Program Executive Committee

Honors/awards:

- 1) Chu was elected Fellow of the Acoustical Society of America (2003)
- 2) Stanton was elected Fellow of the Acoustical Society of America (1996)

- 3) Wiebe was awarded Charles Adams Senior Scientist Chair at WHOI (1996)
- 4) Wiebe was given the NOAA Earth Day Environmental Hero award, May 1999 (by letter from Vice-President Al Gore)

Editorships:

Stanton was Guest Co-Associate Editor for Deep Sea Research Special Topics Issue on Bioacoustical Oceanography, 1998.

Wiebe was Guest Co-Associate Editor for Deep Sea Research Special Topics Issue on Physical-Biological Interactions on Georges Bank and its Environs, 1996.

Wiebe was Guest Co-Associate Editor for Deep Sea Research Special Topics Issue on Coupled Biological and Physical Studies of Plankton Populations in the Georges Bank Region and Related North Atlantic Regions, 2001.

Best Student Paper:

Dan DiPerna, a graduate student on a grant leading to this project, was awarded the "Fye Award" for the best student paper in the Department of Applied Ocean Physics and Engineering for the five-year period 1993-1998. His paper, published in the Journal of the Acoustical Society of America, described his novel theoretical formulation describing acoustic scattering by cylinders of arbitrary cross section.

Graduate students on this project:

- 1) Linda Martin Traykovski (MIT/WHOI, Ph.D., 1998)
- 2) Joe Warren (MIT/WHOI, Ph.D., 2000)
- 3) Gareth Lawson (MIT/WHOI, Doctoral Candidate)

Postdoctoral Fellows on this project:

- 1) Duncan McGehee
- 2) Andone Lavery

Books:

2000 Harris, R., P. Wiebe, J. Lent, H. Skjoldal and M. Huntley (eds). ICES Zooplankton Methodology Manual. Academic Press.

Foote, K.G. and T.K. Stanton, Observing Aquatic Organisms by Sound and Light, Springer-Verlag (accepted).

Chapters in Books:

1997 Stanton, T.K., D. Chu, and P.H. Wiebe, "Ray solutions to sound scattering by complex bodies: application to zooplankton," in Überall Festschrift book, "New perspectives on problems in classical and quantum physics" Part II, eds. P.P. Delsanto and A.W. Sáenz (Gordon and Breach Science Publishers, Amsterdam). Chapter 12.

2000 Foote, K.G. and T.K. Stanton, "Acoustical methods," ICES Zooplankton Methodology Manual. Chapter 6, 223-258.

2000 Skjoldal, H.R., P.H. Wiebe, and K.G. Foote, "Sampling and experimental design," ICES Zooplankton Methodology Manual. Chapter 2. Academic Press. 33-54.

2000 Sameoto, D., P. Wiebe, J. Runge, L. Postel, J. Dunn, C. Miller and S. Coombs, "Collecting Zooplankton," ICES Zooplankton Methodology Manual. Chapter 3. Academic Press. 55-82.

Holliday, D.V. and T.K. Stanton, "Active acoustical assessment of plankton and micronekton," in Sounds in the Sea (Cambridge University Press) by H. Medwin. Chapter 12. (accepted).

Refereed Journal Papers:

1995 Wiebe, P.H., "Developing a high-frequency system to remotely "see" plankton distributions." *Oceanus*, **38**(1), 14-17.

1996 Greene, C.H., J. Popp, P.H. Wiebe, M.C. Benfield, and C. Pelkie, "Three-dimensional acoustic visualization of zooplankton patchiness on Georges Bank." *Deep-Sea Research II*, **43**, CD-ROM Supplement.

1996 Martin, L.V., T.K. Stanton, J.F. Lynch and P.H. Wiebe, "Acoustic classification of zooplankton," *ICES J. Mar. Sci.*, **53**, 217-224.

1996 Stanton, T.K., D. Chu and P.H. Wiebe, "Acoustic scattering characteristics of several zooplankton groups," *ICES J. Mar. Sci.*, **53**, 289-295.

1996 Wiebe, P.H., D.G. Mountain, T.K. Stanton, C.H. Greene, G. Lough, S. Kaartvedt, J. Dawson, and N. Copley, "Acoustical study of the spatial distribution of plankton on Georges Bank and the relationship between volume backscattering strength and the taxonomic composition of the plankton," *Deep-Sea Research II*, **43**, 1971-2001.

1997 Wiebe, P.H., T.K. Stanton, M. Benfield, D. Mountain, and C. Greene, "High frequency acoustic volume backscattering in the Georges Bank coastal region and its interpretation using scattering models," *IEEE J. Ocean. Eng.*, **22**, 445-464.

1998 Benfield, M.C., P.H. Wiebe, T.K. Stanton, C.S. Davis, S.M. Gallagher, and C.H. Greene, "Estimating the spatial distribution of zooplankton biomass by combining video plankton recorder and single-frequency acoustic data," *Deep Sea Res.* **45**, 1175-1199.

1998 Chu, D., and T.K. Stanton, "Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton," *J. Acoust. Soc. Am.* **104**, 39-55.

1998 Greene, C.H., P.H. Wiebe, C. Pelkie, M.C. Benfield, and J.M. Popp. "Three-dimensional acoustic visualization of zooplankton patchiness." *Deep-Sea Research II*, **45**(7), 1201-1217.

1998 Martin Traykovski, L.V., R.L. O'Driscoll, and D.E. McGehee, "Effects of orientation on broadband acoustic scattering of Antarctic krill (*Euphausia superba*): Implications for inverting zooplankton spectral acoustic signatures for angle of orientation," *J. Acoust. Soc. Am.* **104**, 2121-2135.

1998 Martin Traykovski, L.V., T.K. Stanton, P.H. Wiebe, and J.F. Lynch, "Model based covariance mean variance classification techniques: Algorithm development and applications to the acoustic classification of zooplankton," *IEEE J. Ocean. Eng.* **23**, 344-364.

1998 McGehee, D.E., R.L. O'Driscoll, and L.V. Martin Traykovski, "Effects of orientation on acoustic scattering from Antarctic krill at 120 kHz," *Deep Sea Res. II*, **45**, 1273-1294.

- 1998 Stanton, T.K., D. Chu, P.H. Wiebe, L. Martin and R.L. Eastwood, "Sound scattering by several zooplankton groups I: Experimental determination of dominant scattering mechanisms," *J. Acoust. Soc. Am.*, **103**, 225-235.
- 1998 Stanton, T.K., D. Chu, and P.H. Wiebe, "Sound scattering by several zooplankton groups II: scattering models," *J. Acoust. Soc. Am.*, **103**, 236-253.
- 1998 Stanton, T.K., P.H. Wiebe, and D. Chu, "Differences between sound scattering by weakly scattering spheres and finite length cylinders with applications to sound scattering by zooplankton," *J. Acoust. Soc. Am.*, **103**, 254-264.
- 1999 Greene, C.H., P.H. Wiebe, A.J. Pershing, G. Gal, J.M. Popp, N.J. Copley, T.C. Austin, A.M. Bradley, R.G. Goldsborough, J. Dawson, R. Hendershott, and S. Kaartvedt, "Assessing the distribution and abundance of zooplankton: A comparison of acoustic and net-sampling methods with D-BAD MOCNESS," *Deep Sea Res. II*, **45** (7), 1219-1237.
- 1999 Monger, B.C., S. Chinniah-Chandy, E. Meir, S. Billings, C.H. Greene, and P.H. Wiebe, "Sound scattering by the gelatinous zooplankters *Aequorea victoria* and *Pleurobrachia bachei*," *Deep Sea Res. II*, **45**(7), 1255-1271.
- 2000 Orr, M.H., L.R. Haury, P.H. Wiebe, and M.G. Briscoe, "Backscatter of high frequency (200 kHz) acoustic wave fields from ocean turbulence," *J. Acoust. Soc. Am.*, **108**(4), 1595-1601.
- 2000 Stanton, T.K., "On acoustic scattering by a shell-covered seafloor," *J. Acoust. Soc. Am.* **108**, 551-555.
- 2000 Stanton, T.K. and D. Chu, "Review and recommendations for modeling of acoustic scattering by fluid-like elongated zooplankton: Euphausiids and copepods," *ICES J. Mar. Sci.* **57**(4), 793-807.
- 2000 Stanton, T.K., D. Chu, P.H. Wiebe, R.L. Eastwood, and J.D. Warren, "Acoustic scattering by benthic and planktonic shelled animals," *J. Acoust. Soc. Am.* **108**, 535-550.
- 2001 Pershing, A.J., P.H. Wiebe, J.P. Manning, and N.J. Copley, "Evidence of vertical circulation cells in the well-mixed area of Georges Bank and their biological implications," *Deep-Sea Res. II*, **48**, 283-310.
- 2001 Warren, J.D., T.K. Stanton, M.C. Benfield, P.H. Wiebe, D. Chu, and M. Sutor, "In situ measurements of acoustic target strengths of siphonophores, a gas-bearing zooplankter," *ICES J. Mar. Sci.* **58**, 740-749.
- 2002 Lavery, A.C., T.K. Stanton, D.E. McGehee, and D. Chu, "Three-dimensional modeling of acoustic backscattering from fluid-like zooplankton," *J. Acoust. Soc. Am.* **111**, 1197-1210.
- 2002 Warren, J.D., T.K. Stanton, D.E. McGehee, and D. Chu, "Influence of animal behavior on acoustic estimates of zooplankton properties," *IEEE J. Ocean Eng.* **27**, 130-138.
- 2002 Wiebe, P.H., T.K. Stanton, C.H. Greene, M.C. Benfield, H.M. Sosik, T. Austin, J.D. Warren, and T. Hammar, "Biomapper-II: An integrated instrument platform for coupled biological and physical measurements in coastal and oceanic regimes," *IEEE J. Ocean. Eng.* **27**, 700-716.

- 2003 Benfield, M.C., A. Lavery, P.H. Wiebe, C.H. Greene, T.K. Stanton, and N. Copley, "Distributions of physonect siphonulae in the Gulf of Maine and their potential as important sources of acoustic scattering," *Can. J. Fish. Aquat. Sci.* **60**, 759-772.
- 2003 Chu, D., P.H. Wiebe, N.J. Copley, G.L. Lawson, and V. Puvanendran. "Material properties of North Atlantic cod eggs and early-stage larvae and their influence on acoustic scattering." *ICES J Mar Sci.*, **60**(3), 508 - 515.
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- Stanton, T.K., D. Chu, and D.B. Reeder, "Non-Rayleigh acoustic scattering characteristics of individual fish and zooplankton," submitted to *IEEE J. Ocean. Eng.*

Conference Proceedings:

Numerous unrefereed conference proceedings were published during this period. Generally, the content of those works ultimately appeared in some of the refereed papers listed above.

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